Dynamic Analysis of the hFan, a Parallel Hybrid Electric Turbofan Engine

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Outline

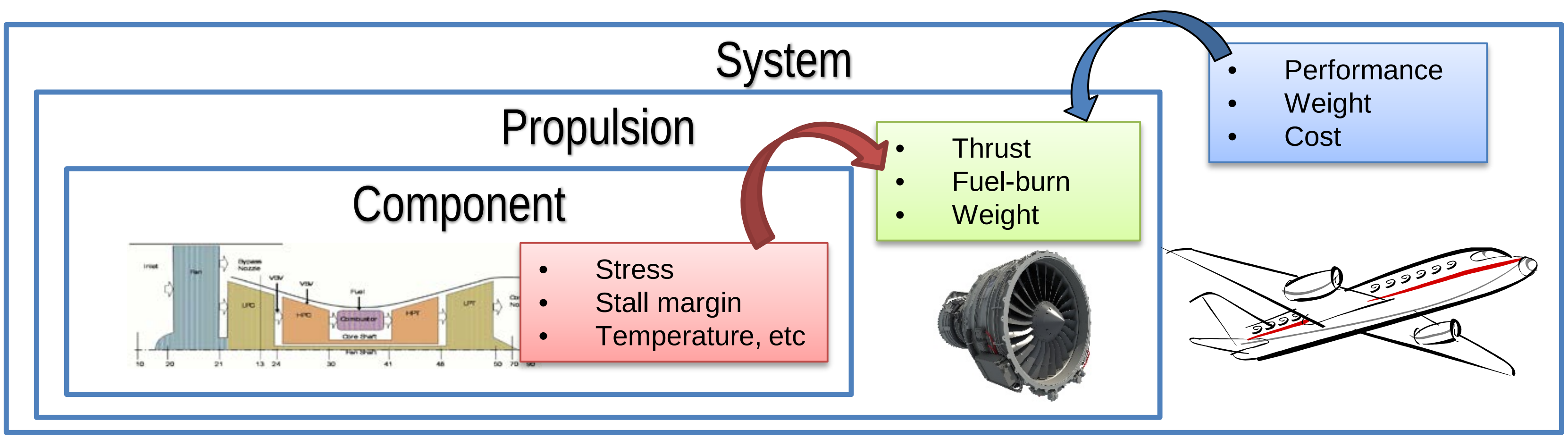
- **Introduction**
  - Motivation
  - Engine Design Process (Systems Analysis)
  - Dynamic Systems Analysis
- NASA hFan
  - Engine
  - Closed-loop system
- Simulation Results
  - Baseline Controller
  - Dynamic Systems Analysis
- Conclusions

Introduction – Motivation

- NASA N+3 commercial aviation goals
  - Targeting 2030-2035 time frame
  - Noise, emissions, fuel burn
- Concept architectures developed to meet goals
- NASA performs research work on these concepts
  - Advanced Air Transport Technologies (AATT) project
  - Systems Analysis and Integration (SA&I) subproject
- Particular concept studied: **SUGAR Volt / hFan**
- Studying hFan can answer general hybrid questions

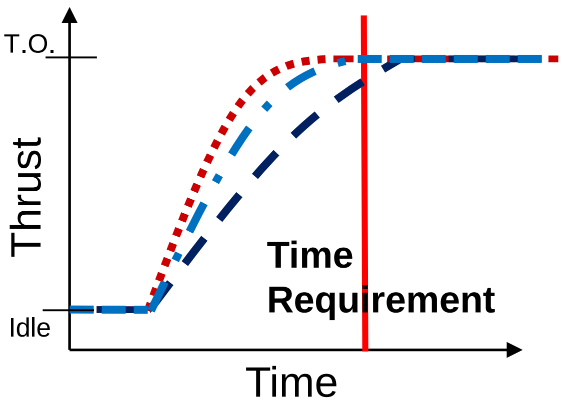
Introduction – Engine Design Process

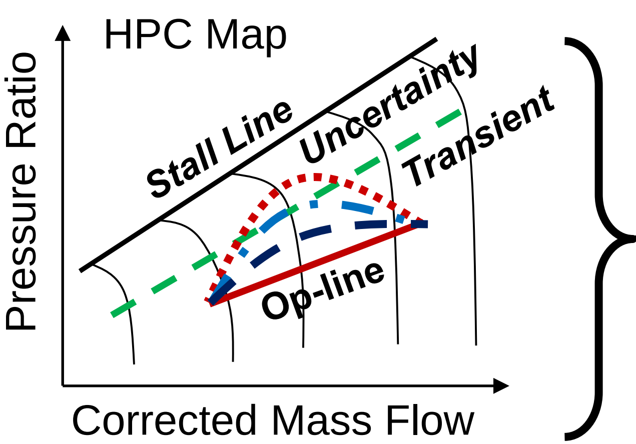
- Engines are designed using <u>systems analysis</u>
  - Steady-state system-level simulations
  - Evaluate system tradeoffs to find optimal designs
- Propulsion systems designed given objectives and constraints
  - Objectives: fuel burn, emissions, noise, cost, performance
  - Constraints: component min/max operating conditions (e.g. stall margins)
  - **Transients** (dynamic) cause engine to run **closer to constraints**
  - Solution is to add **additional margin** to steady-state (design) constraint

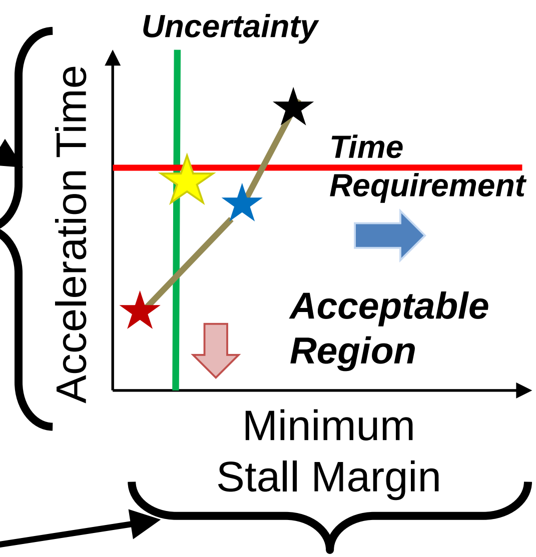


Introduction – Dynamic Systems Analysis

- **Performance** requirement for closed-loop system (Accelerate within 5 seconds)
- Steady-state engine design **operability** constraints include
  - **Uncertainty stack** (how much needed for off-nominal margin debits)
  - **Transient stack** (how much is needed for engine power transitions)
- Controls affects performance vs operability tradeoff



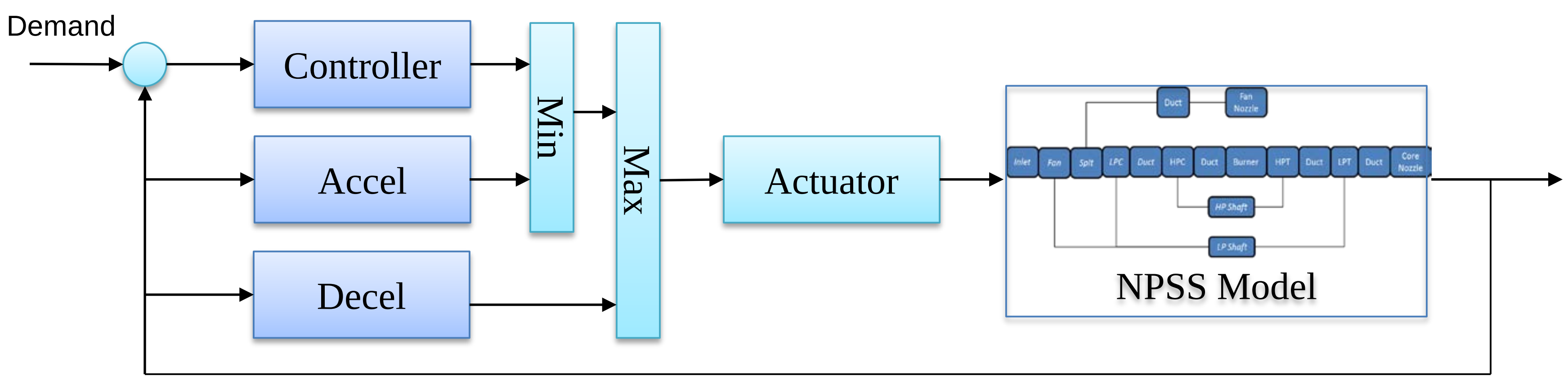




- DSA workflow:
  - Design family of controllers parametrically (using TTECTrA)
  - Simulate resulting closed-loop systems to obtain performance metrics
  - Metrics allow performance and operability trade to be assessed
  - Knowledge of trade enables improvements early in design phase

Introduction – Dynamic Analysis Tools

- Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA)
  - Developed at NASA Glenn Research Center
  - Enables estimation of the closed-loop transient performance
    - https://github.com/nasa/TTECTrA/releases
  - TTECTrA designs controllers to protect engine during transient operation, preserving desired limits (stall margin (HPC/LPC), Fuel to Air Ratio, T40)
- Integrated TTECTrA with NPSS via S-function interface
- Enables dynamic analysis of future engine concepts



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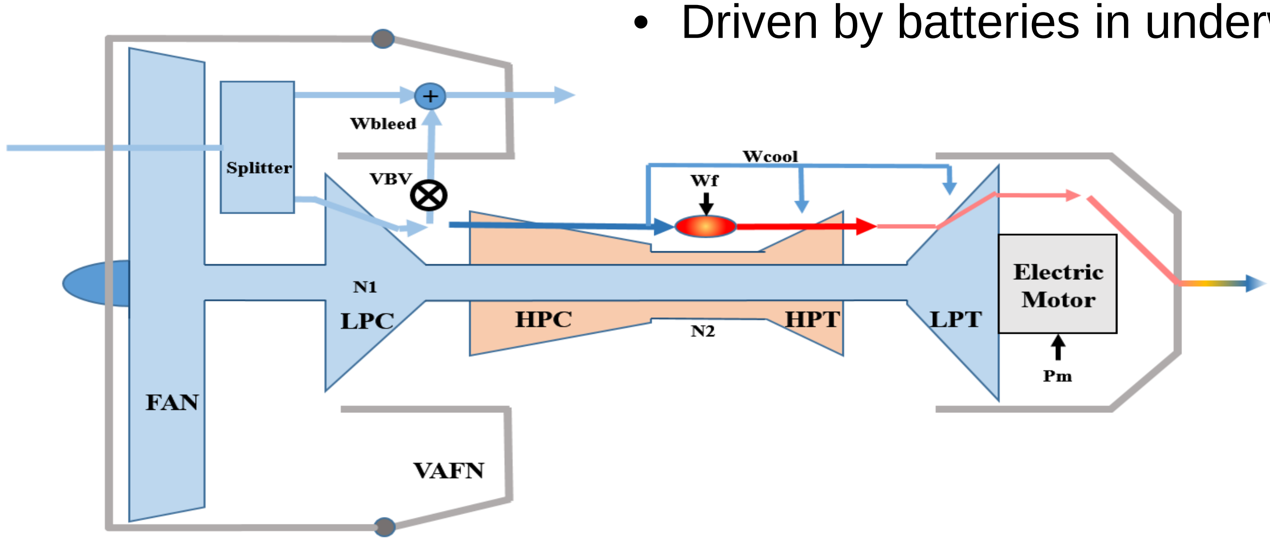
NASA hFan

- NASA hFan (Parallel Hybrid Electric Turbofan, for SUGAR Volt aircraft)

SUGAR Volt

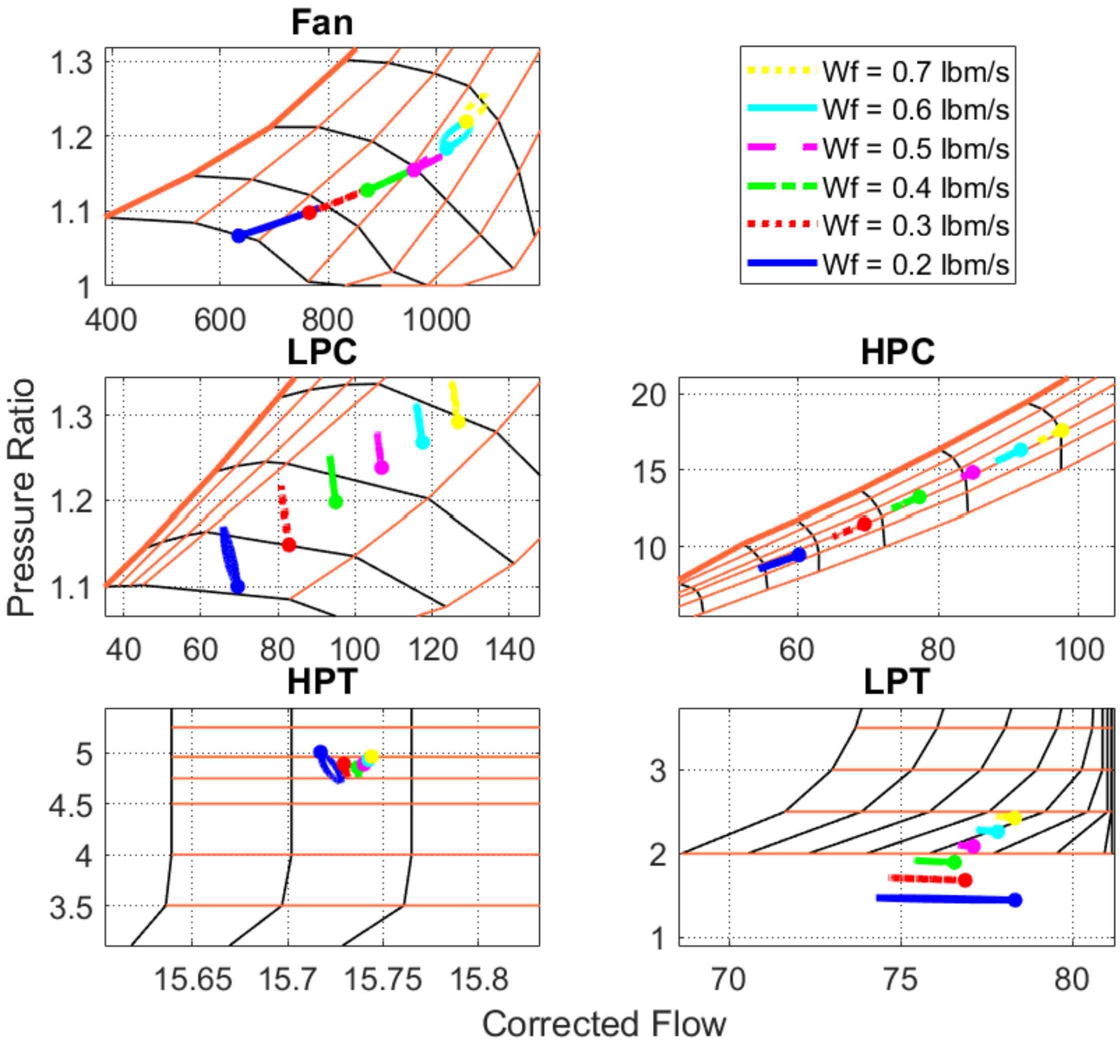
TOGW:	170,000 lbf
Top of Climb Thrust per engine:	3,500 lbf
Takeoff BET required per engine:	17,500 lbf
Takeoff SLST:	20,100 lbf

- Sized for high L/D, TBW, 150 PAX aircraft
  - 3500 mi max mission
  - 900 mi avg/design mission
- Direct drive, two spool turbofan
- N+3 cycle/technology assumptions
- 1380 HP electric machine (EM) on LP spool
  - Assists driving fan for most of flight
  - Driven by batteries in underwing pods



NASA hFan

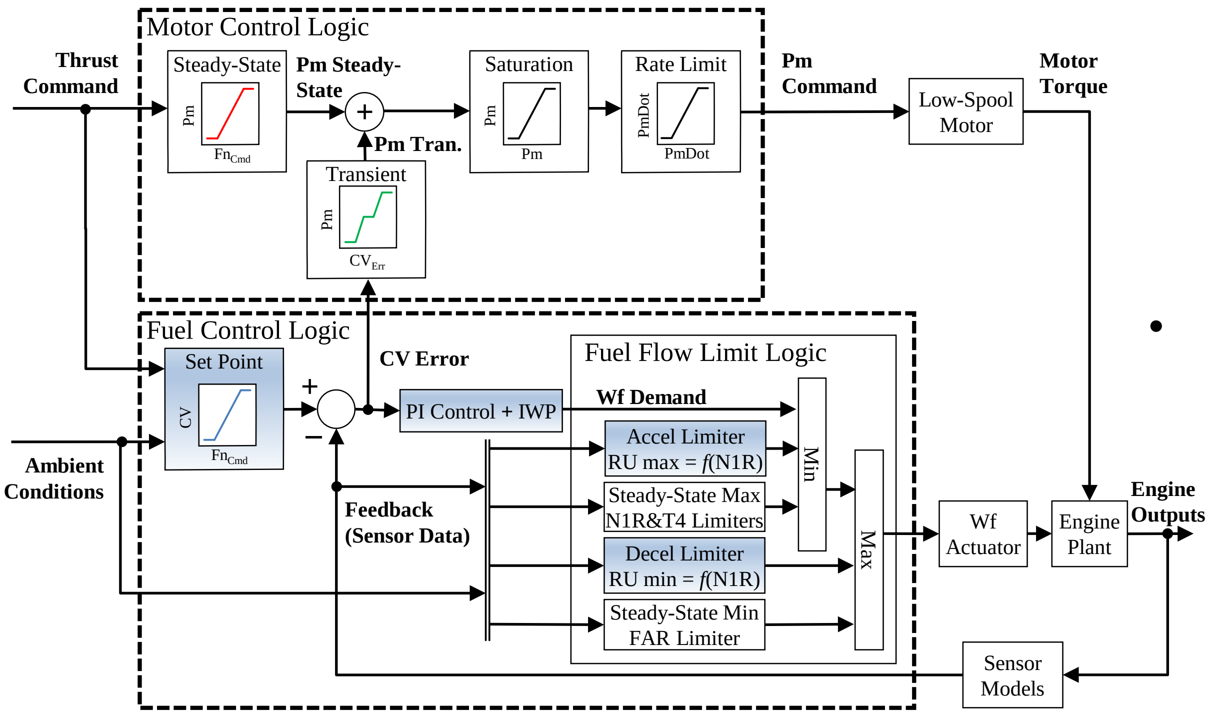
- Q: How does motor make this different from conventional turbofan?
- A: If open loop motor power ramped up and fuel flow held constant…



- Fan goes up op-line
- LPC PR goes up
- HPC goes down op-line
- HPT doesn't really move
- LPT Wc goes down
- Takeaways:
- Adding motor power…
  - reduces LPC stall margin, affords some SM control
  - increases fan corrected speed (increases thrust)
- Control design takes this into account

NASA hFan – Closed-Loop System

- TTECTrA control system revised to control thrust directly
  - Assumes onboard thrust model (model-based engine control, or MBEC)
  - Simplifies control design and analysis, and is appropriate for conceptual study
- Fuel control: Gain scheduled PI with…
  - Accel limiter: Wf/Ps3 max schedule
  - Decel limiter Wf/Ps3 min scalar



- Motor control:
  - Steady-state power = *f*(thrust demand)
  - Additional transient power = *f*(thrust control error)
  - Saturation and rate limit prevent exceeding motor limits
  - Assume maximum assist power delivered instantaneously is best
  - Controller designed to do this
- Baseline control design vars
  - max T4 = 3140 ˚R
  - VAFN variation <= 30% of max
  - min HPC stall margin = 14%
  - min LPC stall margin = 10%
  - min Fan stall margin = 10%

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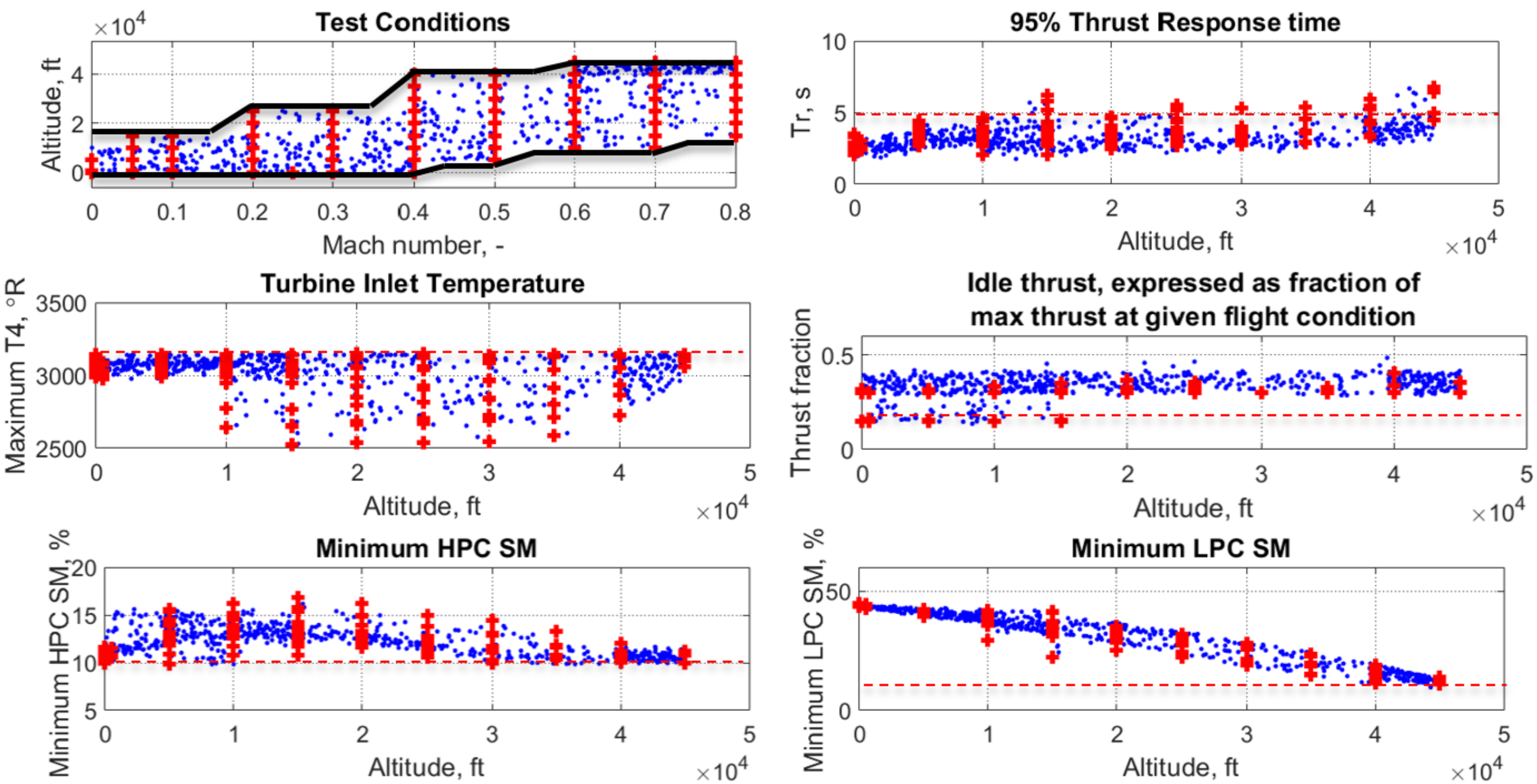
Simulation Results – Baseline Controller

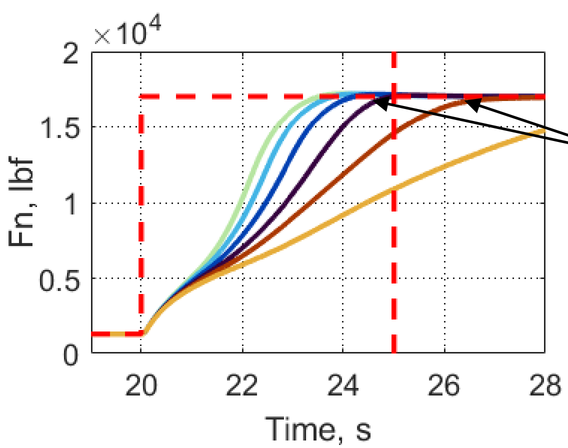
- Analyze transient response of baseline controller
  - Run 15-100% thrust response (accel and decel) at controller design points (red points)
  - Evaluate off-design closed-loop response with Monte Carlo accel/decel simulations (blue)
- Results show closed loop system <u>is operable throughout envelope</u>
  - Satisfies constraints
- Closed-loop system also <u>meets performance requirements</u>
  - Response time less than 5 s when doing a 15-100% transient at static condition



Given baseline system is operable, next step—conduct DSA to learn more about engine

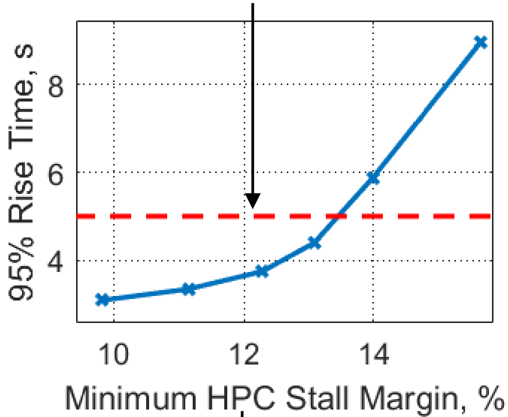
Simulation Results – DSA

- TTECTrA used to tune accel limiters for different HPC stall margin constraints
  - Controllers designed for 5, 7, 9, 11, 13, and 15% minimum HPC stall margin
  - 15-100% snap accel transients ran at sea-level static for each controller
  - Thrust, stall margin responses shown
  - Response time (15% – 95% thrust) and minimum HPC stall margin metrics obtained

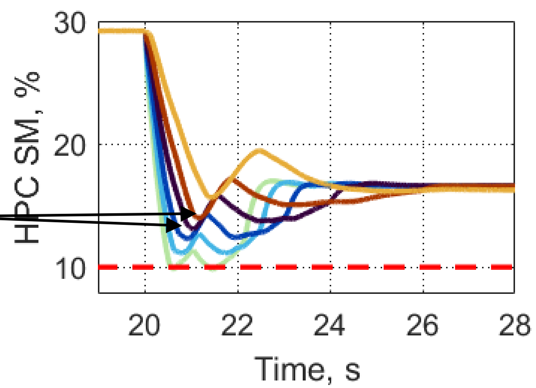


Each line represents response obtained with a different controller (accel limiter)

Compute metrics from response data



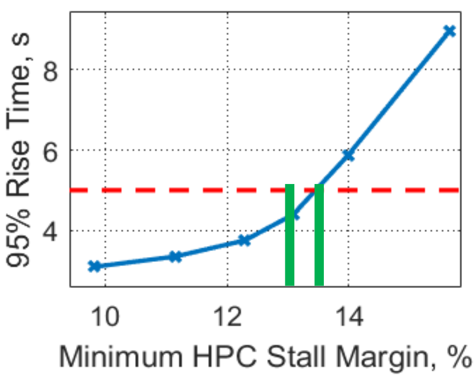
Different controller (time) response gives different minimum HPC stall margin

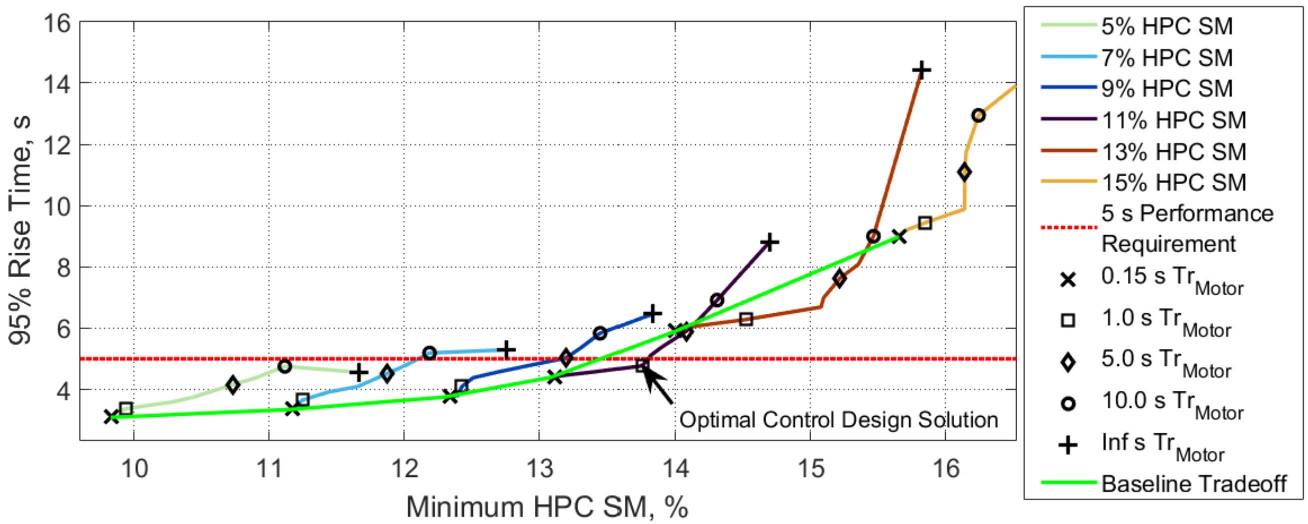


Metrics capture info regarding design tradeoffs, informing design process

Simulation Results – DSA

- Engine can accelerate in 5 s while preserving 13.0-13.5% HPC SM
- However, this assumes baseline motor control design
  - Attempts to apply maximum motor power as soon as the transient begins
- As motor power ramp rate limit was decreased, changes to tradeoff observed
  - Varying both fuel controller accel limiter and motor ramp rate simultaneously yields following metrics





- It turns out if ramp rate chosen such that motor response time is approximately 1 second, we get a better trade (higher stall margin for a 5 second accel)
- Also examined design excursions for motor power rating (not shown; see paper)
  - More transient power not found to be beneficial for hFan system

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Conclusions

- Closed-loop N+3 hFan model demonstrated
  - NPSS model integrated into Simulink-based TTECTrA controller via S-Function
  - System is operable throughout envelope
- Dynamic systems analysis conducted
  - TTECTrA controllers designed to assess performance vs operability
  - Suggests steady-state HPC stall margin can be reduced, and engine redesigned
  - Conduct DSA at more flight and uncertainty conditions to obtain better estimate
- Trends observed (useful information for future work)
  - Holding other things constant, application of low spool motor power…
    - …pushes fan and HPC up and down along their op-lines
    - …pushes LPC PR up and down
  - Instantaneous application of motor power is not optimal for operability
    - Moderate ramp rate that gives a 1 second rise time is appropriate for hFan

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Thank You!!

Questions?